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E. Räumschüssel

Model-Based Control Design of a Flat Modular Linear Stepping Motor

INTRODUCTION

The paper deals with the design process of an optimal control for a special flat modular linear stepping motor embedded in the whole motor design process. Main task of this modular designed motor is to actuate valves, flaps, small tools, sensors and other elements, which can be integrated in devices and equipments. This paper is based on the project VERDIAN (Vernetzte magnetische Direktantriebe) and funded by the Federal Ministry of Education and Research. This work is done in close co-operation with the company Microstep GmbH Sömmerda responsible for the overall modular concept and design.

DESIGN METHODS AND TOOLS

Magnetic circuit design and static optimization are carried out in particular with the objective of
- generation of high forces at high air gap lengths,
- convenient characteristic curves (force, position, electric current),
- high holding forces for clamping the slider in the power-off state.

The dynamic requirements are in particular
- silent running and
- convenient dynamic behavior (oscillatory response).

An important instrument to achieve the static objectives is Finite Element Analysis (FEA). Therefore a static model of the motor is needed. The static optimization of the motor's magnetic circuits is done using the FEA-Tool MAXWELL [1].

In order to design an optimal motor control, dynamics simulation is the appropriate method. For the model-based control design a specific dynamic model is used [3]. This model is adapted to the motor, extended and enhanced.

For accurate modeling of the force- and magnetic flux characteristics, in this design stage the results of static FEA are implemented [1]. Dynamics modeling, simulation and control

optimization are realized by using the tool MATLAB/SIMULINK.
Because changes of the static force-position-curves also affect the motor's dynamic behavior, these changes have to be considered in the control design process. That means, the design of the magnetic circuits' geometry and the control design should not be done separately, if optimal features of the total system are demanded. Figure 1 illustrates this issue. Furthermore certain features, like for instance positioning accuracy, depend on the shape and features of the magnetic circuits and the properties of the used open-loop or closed-loop control.

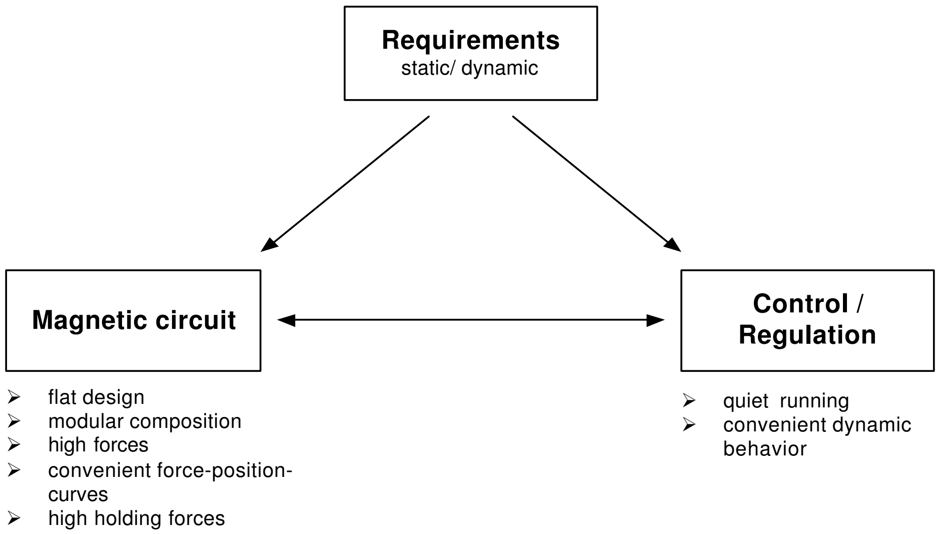

Figure 1: Static and dynamic requirements for the flat modular linear stepping motor

An important point of the model-based design method is to analyze and estimate dynamic behavior and to develop suitable corresponding control procedures parallel to the design process of the motor composition (mechanical and magnetic circuit layout).
Parameters of the dynamics model thereby are continuously updated according to the state of the motor's static optimization process (see also [2]).

CONTROL DESIGN AND MODEL

Figure 2 shows the basic dynamics model of one single phase of the two-phase linear stepping motor [3].

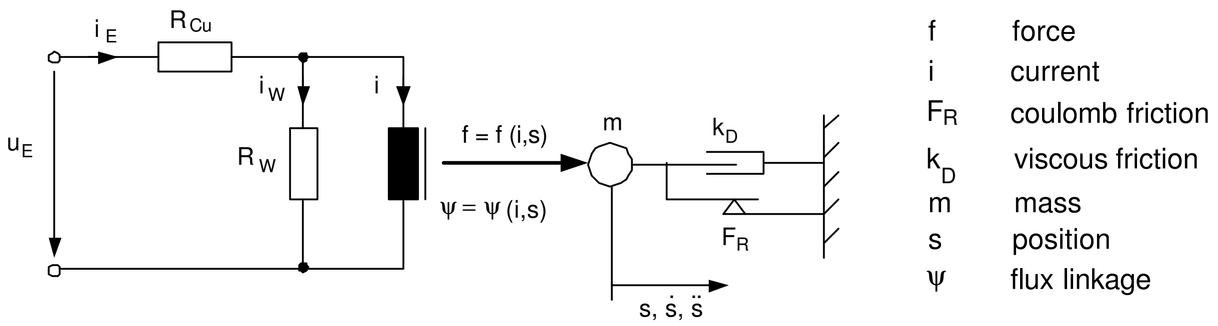

Figure 2: Basic model of the linear stepping motor (one phase)

The equations of the electric circuit of one motor phase are

$$u_E = i_E \cdot R_{Cu} + \frac{d\psi\,(i,s)}{dt} \ , \tag{1}$$

$$i_W \cdot R_W = \frac{d\psi\,(i,s)}{dt} \quad \text{and} \tag{2}$$

$$i_E = i_W + i \ . \tag{3}$$

From equations (1) to (3) we can derive the terminal voltage of one phase u_E

$$u_E = R_{Cu} \cdot i + \frac{R_{Cu} + R_W}{R_W} \cdot \frac{d\psi\,(i,s)}{dt} \tag{4}$$

and for the magnetic flux linkage ψ follows

$$\psi = \int (u_E - R_{Cu} \cdot i) \cdot \frac{R_W}{R_{Cu} + R_W}\, dt \ . \tag{5}$$

The input current i_E of the motor phase is

$$i_E = (u_E - \frac{d\psi\,(i,s)}{dt}) \cdot \frac{1}{R_{Cu}} \ . \tag{6}$$

The motor force is given by

$$f(i,s) = m \cdot \ddot{s} + k_D \cdot \dot{s} + F_R\, sign(\dot{s}) \ . \tag{7}$$

With respect to the motor's force generation the above-described model represents a quasi-static model. Especially eddy currents (Resistor R_W, partially contained also in Damping k_D) as well as core losses (partially contained in F_R) are taken into account to complete the motor's dynamic features.

For the design of our flat modular lnear stepping motor this model is advanced and well adapted. Within the design and optimization process of the motor's magnetic circuits, see [1], the characteristics of flux, current and position were additionally calculated as functions of the air gap lengths δ, in the same way the force-current-position-characteristics. Thereby we get the possibility to analyze the influence of the normal forces, too.

For the simulation model the associated data set is conditioned as three-dimensional look-up tables $f=f(i,s,\delta)$ and $\psi=\psi(i,s,\delta)$. Figure 3 shows the data structure ("δ-slices" as matrices) of the motor forces f for m position values, n current values and k values of air gap lengths.

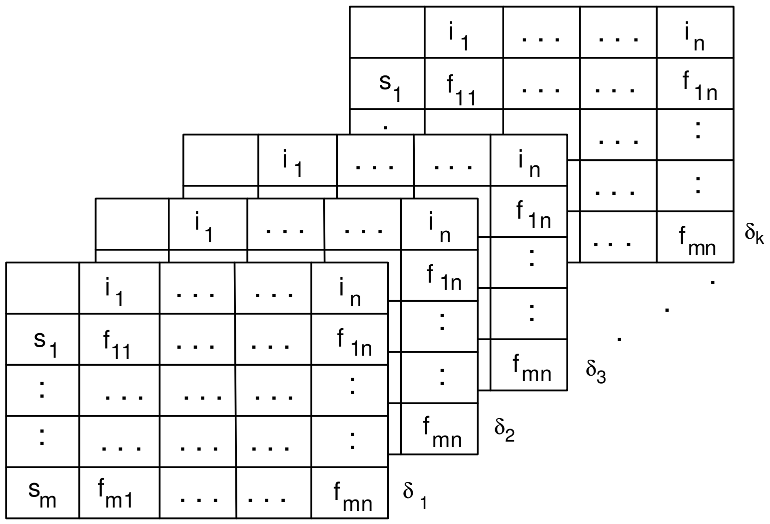

Figure 3: Force-position-current-characteristics with different air gap lengths

The data sets of the magnetic flux-position-current-air gap length-characteristics have the same structure, but for their use in simulation they have to be converted into $i=i(\psi,s,\delta)$. The values of s, i, δ, f and s, ψ, δ, i are sampling points in the look-up tables. During the simulation run of the moving motor it is interpolated between all values (virtually in space, see Fig. 3).

SIMULATION STRUCTURE (SIMULINK) OF THE MOTOR

The MATLAB/SIMULINK simulation model of the motor is derived from equations (1) to (7). Fig. 4 shows the partial model (section) for calculating the current and force of phase A as well as the motion generation. Phase B has the same structure. The look-up tables are highlighted in colors.

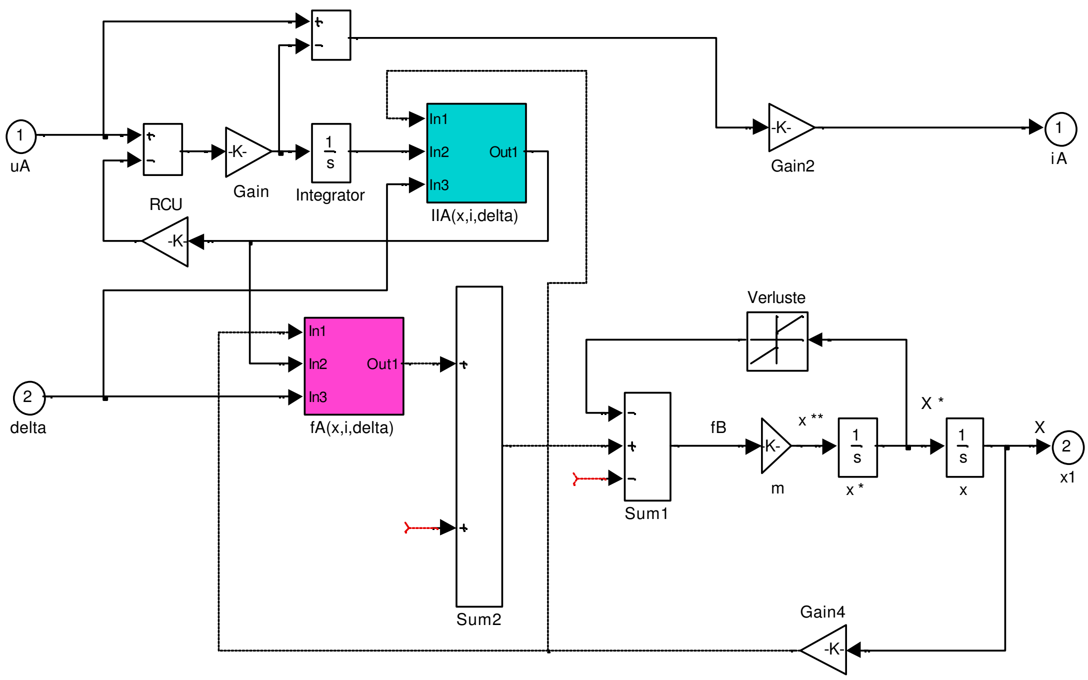

Figure 4: SIMULINK-Model of the flat modular linear motor, section of driving force creation and motion generation of one phase (x-direction)

Fig. 5 illustrates the creation of the normal forces and corresponding acceleration, velocity and displacement (y-direction).

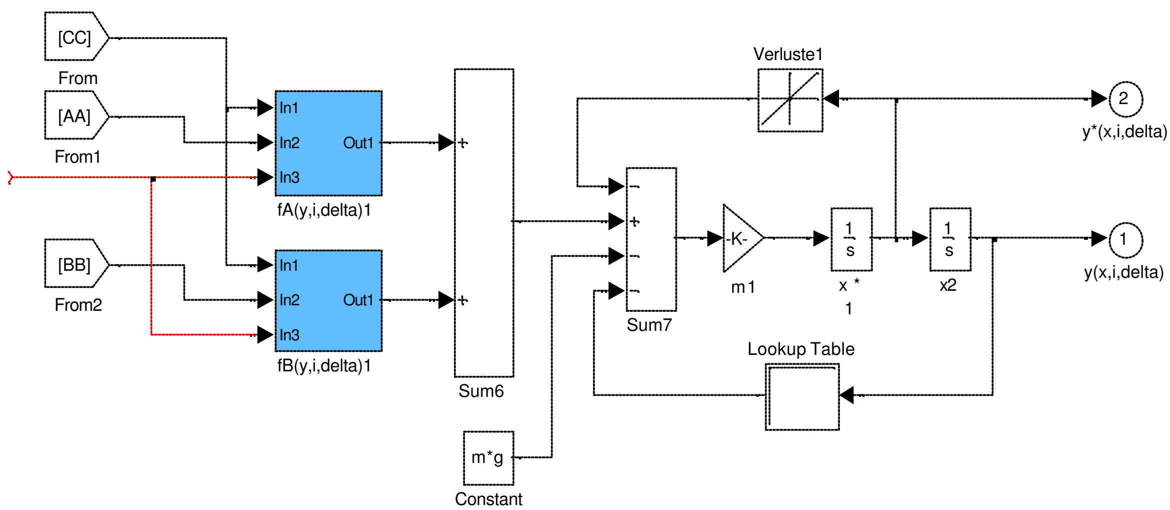

Figure 5: SIMULINK-Model of the flat modular linear motor, section of normal force creation and corresponding motion in normal (vertical) direction

The Inputs In3 of the look-up tables obtain the values of the air gap lengths δ. Output value y of the partial model in Fig. 5 is the position in normal direction. The one-dimensional look-up table in the Figure represents the stiffness of the guidance in this direction. This depends on the special application of the motor. Currently the simulation is done using estimated values of these parameters.

For the idle motor the position y is equal to the air gap length δ. By feedback of y to the inputs In3 of the look-up tables in Fig. 4, the influence of the change of the air gap length on the driving force of the running motor can be analyzed.

SIMULATION MODEL OF THE DRIVE CONTROL

Based on the motor's mathematical model, a corresponding simulation model for controlling the motor is designed.

This model allows simulation tests and investigations for different applications and optimal operations of the motor for

- full-step, half-step and micro-step operation mode,
- voltage control and current control (regulation),
- different air gap lengths, loads and motor guides.

The approved simulation structure for voltage control of the motor is shown in Fig. 6.

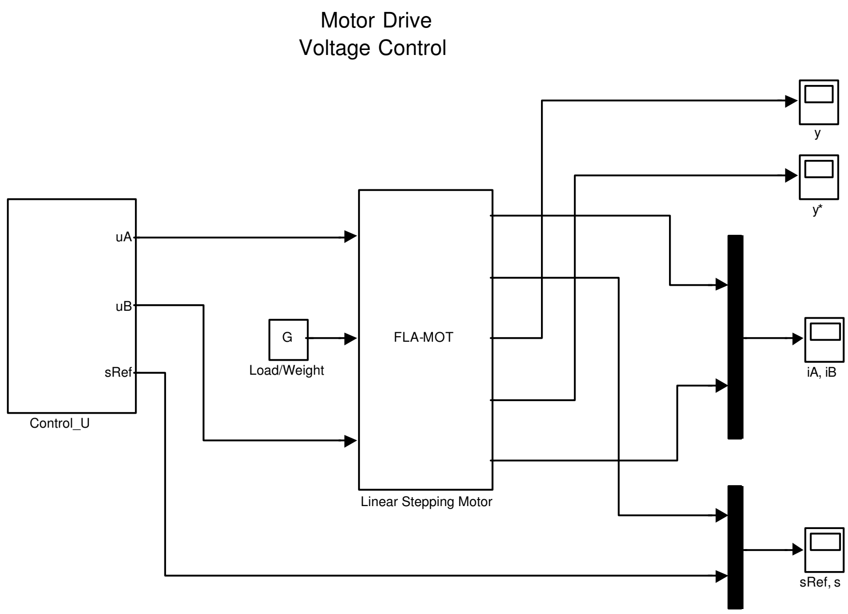

Figure 6: SIMULINK-Model of the stepping motor drive with voltage control

The block Control_U outputs the signals of the motor's terminal voltages of the phases u_A and u_B. As simulation results, the signals of required position s_{Ref} and actual position s are

monitored for comparison, and the characteristics of the phase currents i_A and i_B as well as the position variation y and velocity y* perpendicular to the drive direction are displayed.
Figure 7 shows the simulation structure of the drive system with current control (closed-loop control).

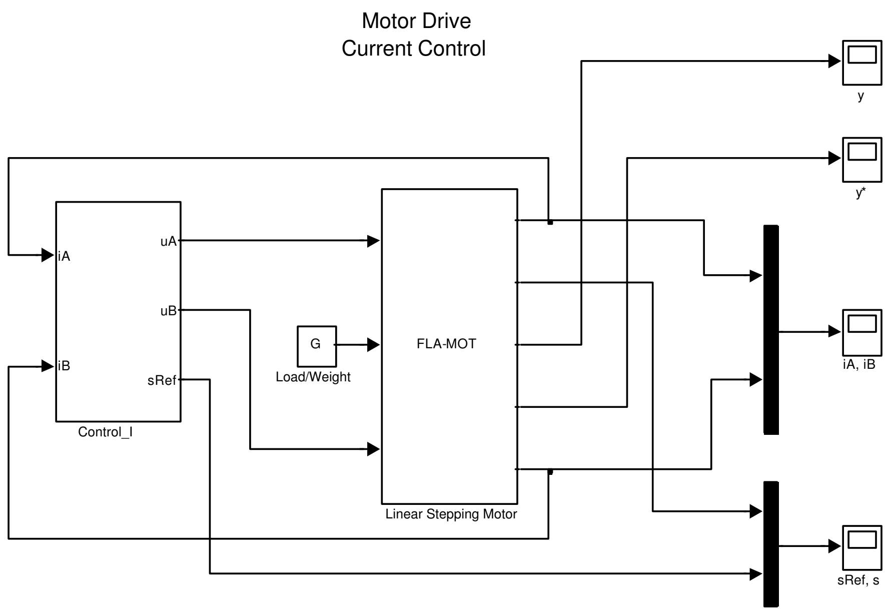

Figure 7: SIMULINK-Model of the drive with current control

The control blocks (U,I) in Fig. 6 and Fig. 7 are designed at present for start-stop-positioning (pull-in mode) with variable frequency, step-width and step-number. They can easily be changed for the use of other desired motion characteristics.
The blocks Control in Fig. 6 and Fig. 7 also contain the voltage- and current inverters; but they are not to be discussed more detailed in this paper.

RESULTS – EXAMPLES OF SIMULATION TASKS

Because the modular linear motor can be used for different tasks and also in very different areas of application, no strong requirements of motion characteristics and typical loads can be defined. Rather they can vary in a wide range.
On the base of the designed models and simulation programs, suitable (optimal) control methods for different existing loads (friction, damping, guide- and bearing-reactions or other special loads) and special requirements of application can be determined. In particular
- closed-loop current control,

- voltage control,
- full-step, half-step and micro-step operation with different numbers of substeps,
- different air gap lengths for special applications in various devices

can be taken into account.

Furthermore quasi-static characteristics can be analyzed. For instance, the values of the holding forces for clamping the slider in the power-off state can be found out.

Exemplary, the Figures from 8 to 10 show simulation results of positioning operations with the same step frequency and the same travel distance. The load parameters are also the same (estimated on the base of experiences and manufacturer's data).

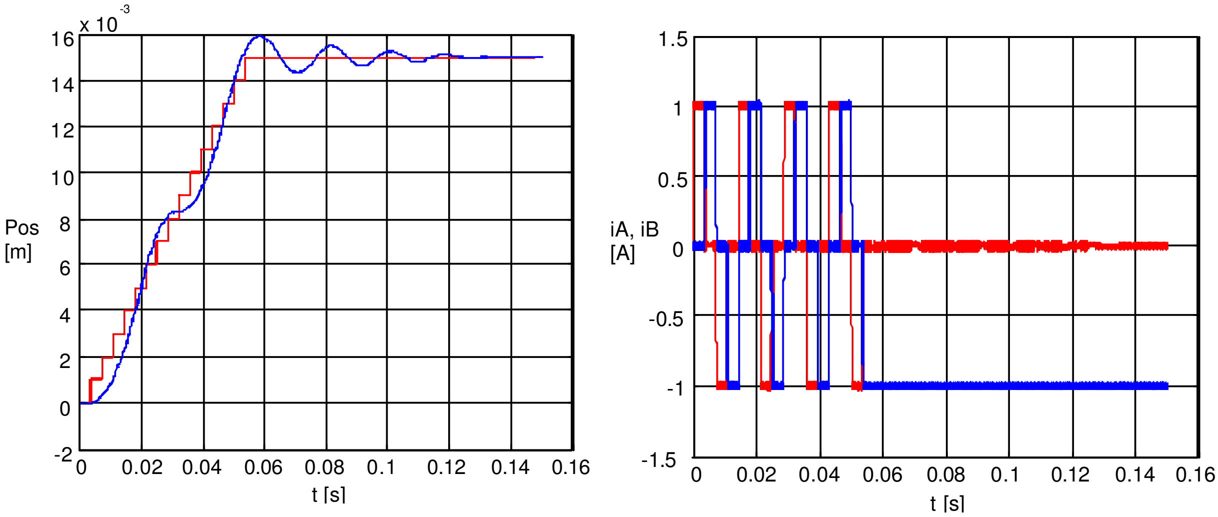

Figure 8: Start-stop-positioning (pull-in mode) with current control, full-step-operation

In the left figure we see the characteristics of the commanded position (red) and the actual position (blue). The right figure shows the corresponding current-characteristics of phase A (red) and phase B (blue).

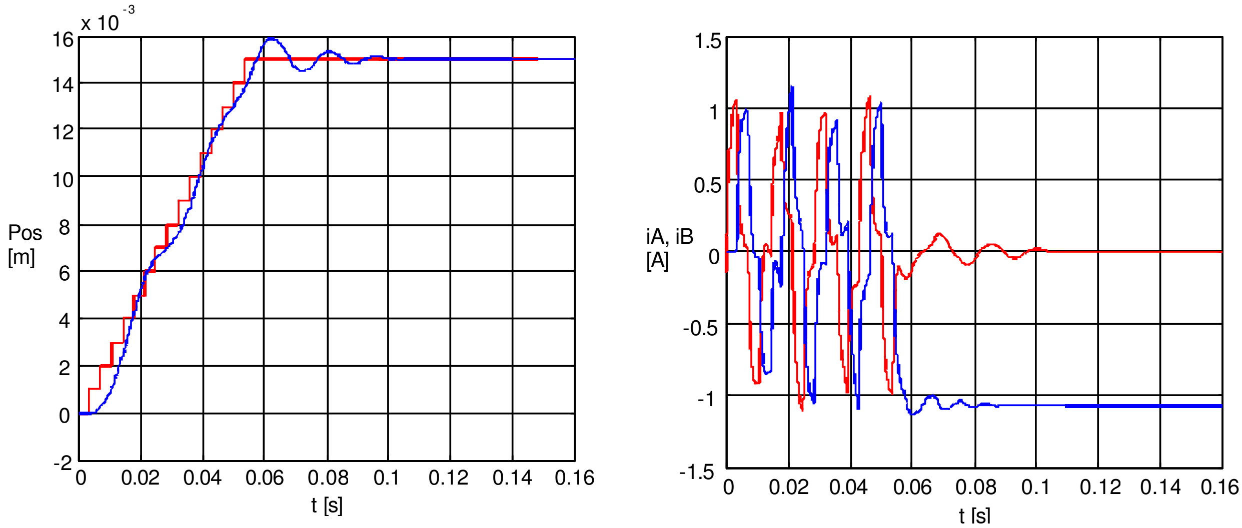

Figure 9: Start-stop-positioning of the motor with voltage control, full-step-operation

In Fig. 9 we can recognize a huge deviation of the current characteristics from the rectangular shape, caused by the inductances and induced e.m.f. The comparison of the position characteristics in Fig. 8 and Fig. 9 shows, that slider oscillations are slightly more damped with voltage control than with current control.

At the end, in Fig. 10 a positioning operation with current control and micro-step mode is shown where one full step is divided into 4 sub-steps.

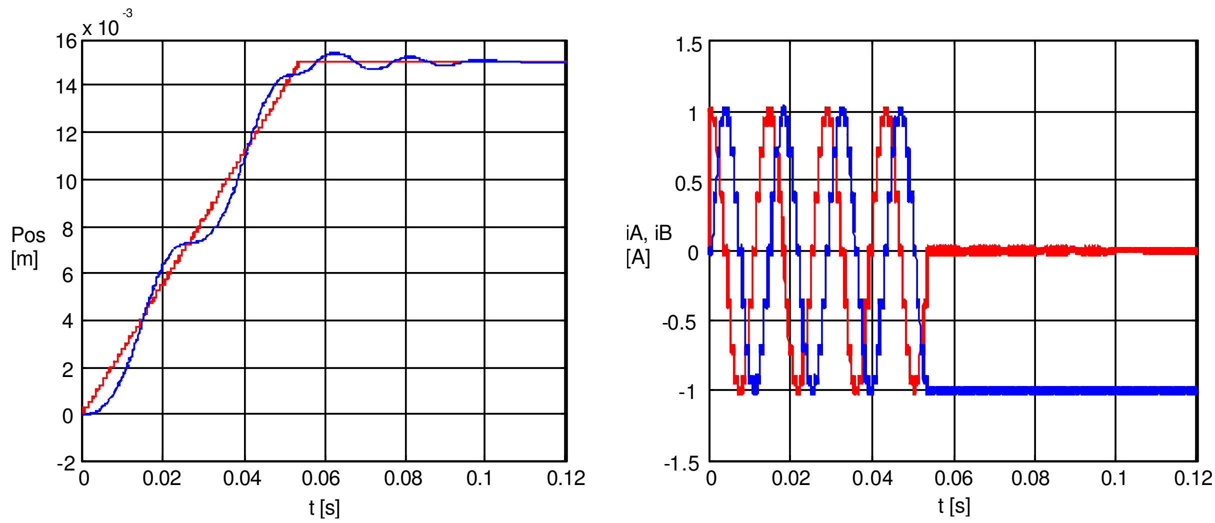

Figure 10: Start-stop-positioning of the motor with current control, micro-step-operation (step angle 1/4 of natural step)

The results of the simulation tasks done until now show that the described models and simulation structures meet all demands concerning the above-asked requirements and targets with respect to optimal control methods and different applications.

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